Gravitational waves

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Gravitational-wave paleontology

N&V article on the paper by Abbott et al.

A new detection of gravitational waves from the merger of two black holes helps unearth the history of the stellar monsters that left them behind.

Just after 2 AM on January 4, 2017, the Advanced Laser Interferometer Gravitational-wave Observatory (aLIGO) detector located in Hanford, Washington, registered a tiny ripple in the fabric of spacetime. Three milliseconds later the twin aLIGO detector located some 3,000 km away in Livingston, Louisiana, picked up an identical chirp. Together, the two signals -- each a stretching and squeezing of space by less than one part in 10^{21} -- constituted the discovery of a third clear (and fourth likely) gravitational-wave source, GW170104[1].

This signal, like all those previously detected, was emitted during the merger of two black holes. The combined mass of GW170104's black holes was about 50 times larger than the mass of the Sun, making it the second heaviest merger observed to date. At a distance of 3 billion light years, it is the farthest confident detection. Although the detected signal was tiny, some 2 solar masses' worth of energy was emitted in gravitational waves: in the last second before merger, the gravitational-wave luminosity of GW170104 exceeded the combined luminosity of all the stars in the visible Universe.

These gravitational waves precisely probe the ultra-strong gravity in the vicinity of black holes. Abbott et al.[1] confirm that there is as yet no evidence contradicting the null hypothesis that Einstein's general theory of relativity explains both the dynamics of merging black holes and the subsequent propagation of gravitational waves through space.

In addition to testing fundamental physics, gravitational-wave astronomy is a promising tool for exploring the Universe via the dramatic fates of its stellar fossils. From the observed events, the LIGO team determined that roughly 1 to 20 pairs of black holes merge every million years in a Milky-Way sized galaxy. Although the observed merging black holes appear to be roughly uniformly distributed in mass, this is partly due to LIGO's greater sensitivity to heavier black holes; the underlying mass distribution is inferred to be skewed toward lower-mass black holes, consistent with the initial mass distribution of massive stars.

How did these black holes come to merge? We do not yet know, but several possibilities have been proposed. The discovery of GW170104 will aid in identifying the dominant pathways.

Though intense near the moment of merger, gravitational waves are quite weak in more widely separated systems. The time to merge via the emission of gravitational waves scales with the fourth power of the separation between orbiting bodies. For the two black holes responsible for GW170104 to have merged in the age of the Universe, they must start out at a separation no larger than a fifth of the distance from the Earth to the Sun. But the massive stars that collapse into such black holes are believed to expand to much larger sizes during their evolution. So how can once huge stars fit into such close quarters without merging into a single star before forming black holes?

Figure 1 illustrates a few of the proposed possibilities. One scenario is that the two stars start out far apart. As the stars expand, the companions' gravity distorts and rips off the outer layers. This can produce a thick envelope of gas around the pair. Friction against this gas brings the dense centers of the stars closer[2,3]. Another scenario is that the stars start very close together and don't expand after all. Instead, rapid rotation sustained by the energetically favorable locking of stellar rotation to the orbital period causes efficient mixing within the stars, allowing them to fuse nearly all of their hydrogen into helium and contract as they evolve[4,5]. Or perhaps the two black holes didn't start out as a pair at all; instead, long after the stars collapsed to black holes, interactions with other stars in a dense stellar cluster brought them close enough for gravitational-wave emission to take over[6,7]. Even more extraordinary possibilities, not illustrated in Figure 1, include non-stellar origins for the two black holes. Could they be formed from the direct collapse of density perturbations in the early Universe[8]?

GW170104, together with previous observations, begins to provide tantalizing hints about which formation channels are most likely. Merger rates alone are not very constraining at present because of uncertainties in all the formation models. The mass distribution of merging black holes will provide more stringent constraints once more detections are available. One particularly interesting piece of evidence from GW170104 relates to the rotation of the black holes. Although the individual rotation frequencies and directions of the two black holes are very difficult to measure, it is clear that there was no significant net rotation in the same direction as the orbit. The two black holes were either very slowly spinning, or were significantly misaligned with the orbit. Misaligned spins could point to the dynamical formation channel (Figure 1c), where black hole spins are expected to be randomly oriented relative to the orbit[9]. However, the evolution of isolated pairs of stars may yield low rotation rates, or misalignments through the birth kicks that compact objects receive during supernovae[10] (Figure 1a).

One thing is clear: mergers of pairs of compact objects will be observed in ever greater numbers as LIGO's sensitivity increases. These will provide a rich and fascinating astrophysical data set. Like paleontologists using fossilized dinosaur skeletons to make inferences about dinosaur appearance, diet, and behavior, we are beginning to use gravitational waves from compact stellar remnants to explore the lives – and deaths – of massive stars.

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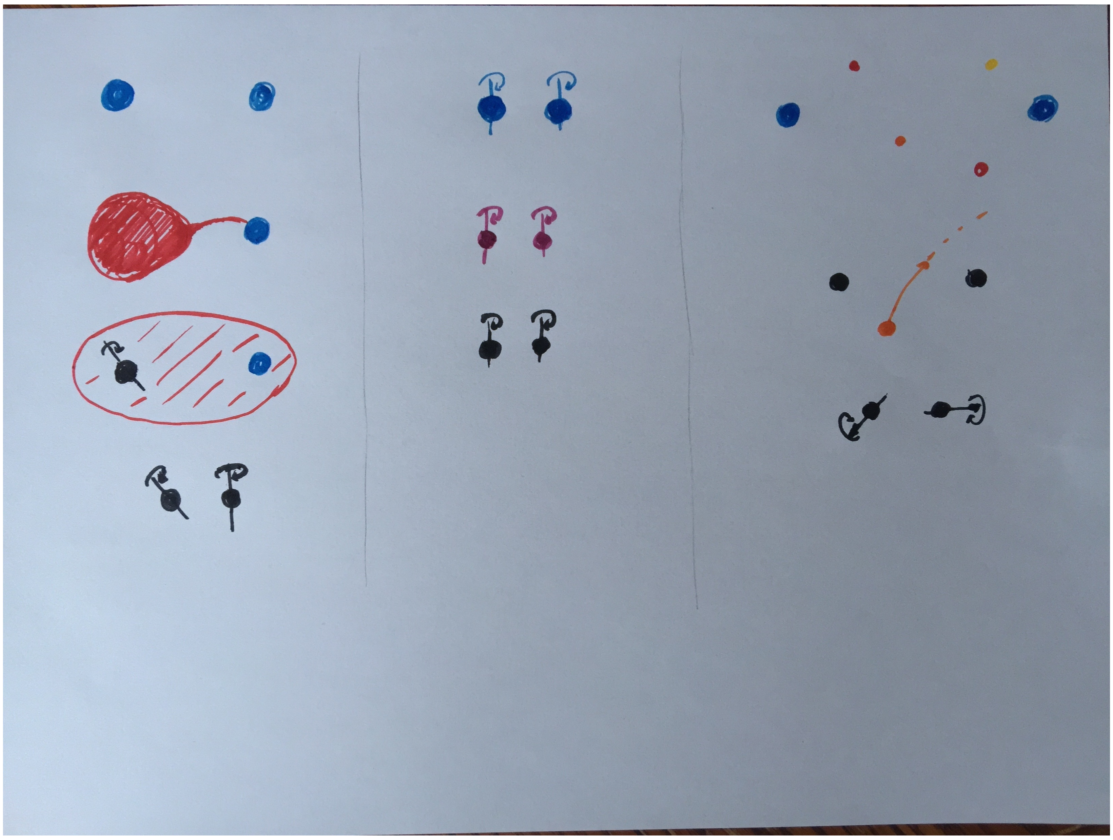
Figure 1:



An illustration of the possible channels for forming merging black holes like GW170104. On the left (1a), two stars that start far apart expand as they age, interact by transferring mass, and are brought closer by friction against a common envelope of gas; the black holes may rotate in the same direction as the orbit, or may be tilted, e.g., by kicks received during asymmetric supernovae. In the middle (1b), stars that start very close together are kept from expanding by rapid rotation and efficient mixing, avoiding mass transfer. On the right (1c), the two black holes are brought together by dynamical interactions with other stars in a dense cluster; their rotation axes are expected to be randomly oriented.